

DRAFT

67016

Feldspathic Fragmental Breccia

4262 grams

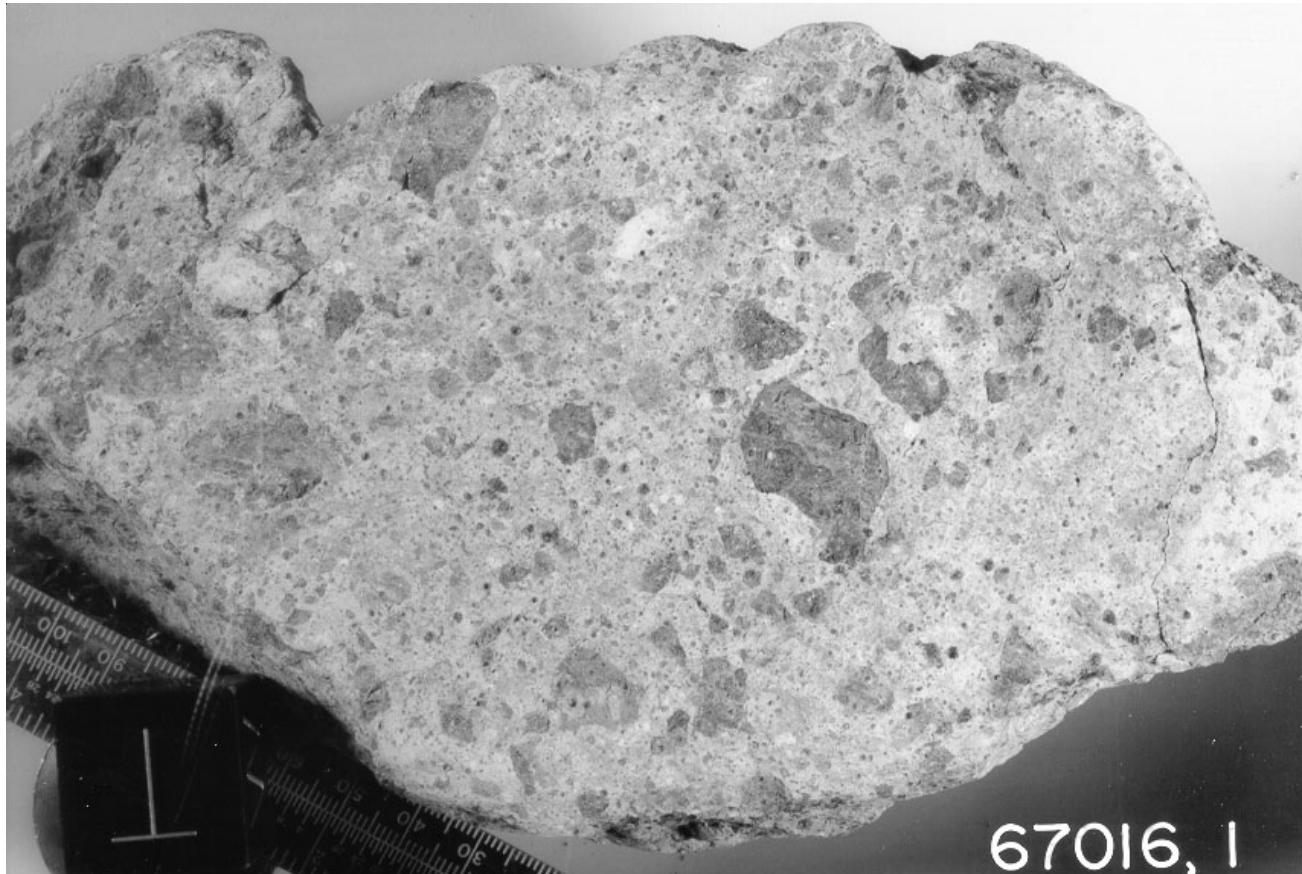


Figure 1: Photo of 67016, I. Cube is 1 inch. NASA # S81-26050.

Introduction

67016 is a feldspathic fragmental breccia with both light and dark clasts (figure 1) collected from the lip of North Ray Crater (Ulrich 1973, Muehlberger et al. (1980). This large rock is thought to be analogous to terrestrial suevite (impact breccia). It is *not* a regolith breccia, because it has relatively low Ni, Ir and Au, low rare gas content and low maturity (I_s/FeO).

67016 is 3.95 b.y. old with an exposure age of 50 m.y. (the apparent age of North Ray Crater). It contains, as a plutonic igneous clast, the oldest lunar sample dated (4.56 b.y.). It also contains a trace-element-rich clast termed “sodic ferrogabbro” as well as numerous other lithic clasts.

The breccias from North Ray Crater are diverse in nature; as are the clasts in 67016 (Lindstrom and Salpas 1983).

Petrography

Nord et al. (1975) describe 67016 as a porous breccia with dark-lithic clasts and lighter plagioclase fragments. The porous light-colored matrix that envelopes the clasts consist mostly of plagioclase with minor pyroxene and olivine. Ilmenite is polycrystalline and heavily deformed. Nord et al. reported that “small 100 micron granitic fragments were very common in the matrix and have reacted with the matrix to produce narrow pyroxene reaction rims”.

Norman (1981) provided an overview of the petrography of 67016 and determined that it is



Figure 2: Photo of clast and matrix in 67016,277. NASA # S82-27849. Size of clast is about 1.5 cm.

analogous to a terrestrial suevite. It is a light-gray breccia with approximately 20% dark melt clasts and 10% white lithic clasts (2 to 5 cm) and scattered single grains of plagioclase, mafic minerals and rare opaques set in a fine-grained, seriate matrix. The lithic clasts include feldspathic granulitic impactite, ferroan anorthosite, subophitic impact melt and a variety of other types. According to Norman (1981), the matrix around metal grains in 67016 is stained a dull orange (rust?). Hunter and Taylor (1981) also reported abundant rust(?) on metal grains in 67016.

Micrometeorite craters and surface patina are reported on unabraded exterior surfaces (Ryder and Norman 1980 and Norman and Garcia 1981) and indicate that the rock was “tumbled” on the lunar surface.

Takeda et al. (1990) compared 67016 with lunar meteorite Y86032.

Norman et al. (1991) and Norman and Taylor (1992) describe sodic noritic anorthosite clasts in 67016. One of these (.326/8) was dated to be very old (Alibert et al. 1994).

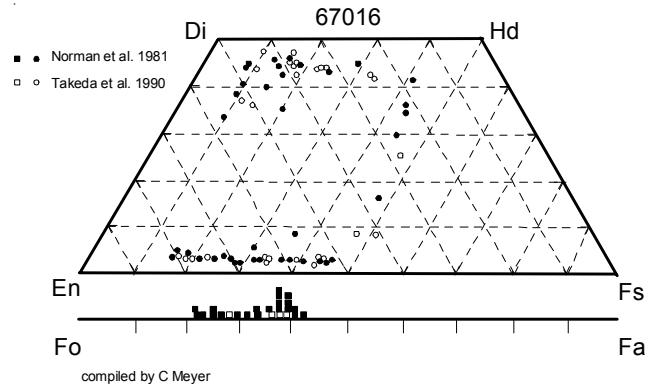


Figure 3: Pyroxene and olivine composition of clasts in 67016 (from Norman 1981 and Takeda et al. 1990).

Lindstrom and Salpas (1981) analyzed a unique clast they termed “sodic ferrogabbro”. Norman (1981) terms this material “ilmenite-silica” gives the mode and mineral compositions (figure 5).

Mineralogy

Olivine: The olivine in 67016 ranges in composition from Fo_{58} to Fo_{78} .

Ilmenite: Nord et al. (1975) found that minor ilmenite in 67016 was polycrystalline.

Plagioclase: Norman (1981) determined the composition of numerous plagioclase grains in the matrix, melt breccia, granulitic clasts and plutonic clasts. The plutonic clasts were An_{95-98} while matrix etc. ranged from An_{82-98} .

Pyroxene: Norman (1981) and Takeda et al. (1990) determined the composition of pyroxene grains in clasts and matrix of 67016 (figure 3).

Metallic Iron: with rust(?)

Mineralogical Mode

Norman 1981

| | |
|---------------------|-----------|
| Mineral Fragments | |
| Plagioclase | 33 vol. % |
| Mafic | 3 |
| Opaques | 1 |
| Melt breccia clasts | 23 |
| Rock Clasts | 11 |
| Matrix | 29 |
| Other | 1 |

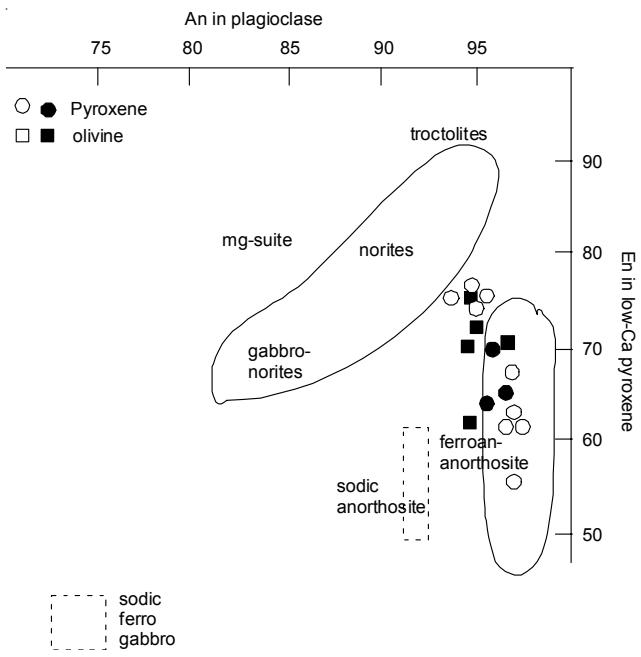


Figure 4: Composition of plagioclase and mafic minerals in clasts in 67016 (from Norman 1981, Takeda et al. 1990, Norman et al. 1991). Trends are from Paul Warren and/or Odette James.

Chemistry

Norman and Taylor (1992) determined the composition of many units and clasts in 67016. Note that their analyses for K, U and Th for a bulk sample (2.2 grams) agrees with the radiation counting by Eldridge et al. (1975) for a 482 gram piece (table 1a). They also give an analysis of the ferroan noritic anorthosite clast that they dated (.326/8). Lindstrom and Sulpas (1983) also analyzed a large number of splits of 67016 (table 1b), including a rare-earth-rich “sodic ferrogabbro clast” (.289, figure 5).

Gibson and Chang (1974) found a trace of carbonate in 67016 by temperature release (figure 7) and determined the isotopic composition of carbon and oxygen. However Gibson and Andrawes (1978) only found nitrogen by crushing.

Meteoritic siderophiles are moderately abundant ($\text{Ir}=1\text{-}3\text{ ppm}$), but less than for a regolith breccia (Hertogen et al. 1977).

Radiogenic age dating

Turner and Cadogen (1975) and Alibert et al. (1994) have dated materials from 67016. Turner and Cadogen determined an age of 3.95 ± 0.07 b.y. for a dark clast

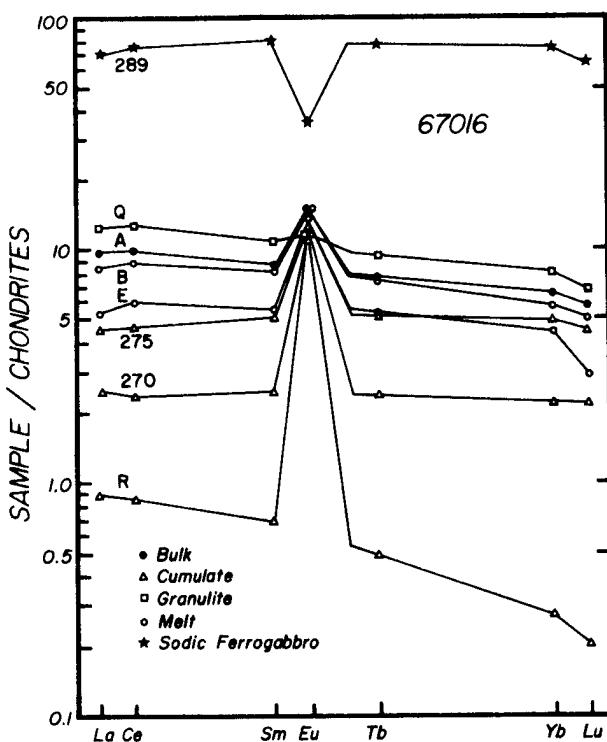


Figure 5: Normalized rare-earth-element diagram for clasts and “bulk” in 67016 studied by Lindstrom and Sulpas 1983.

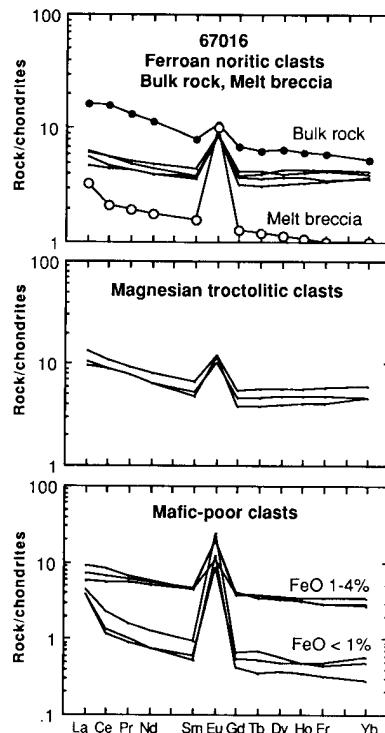
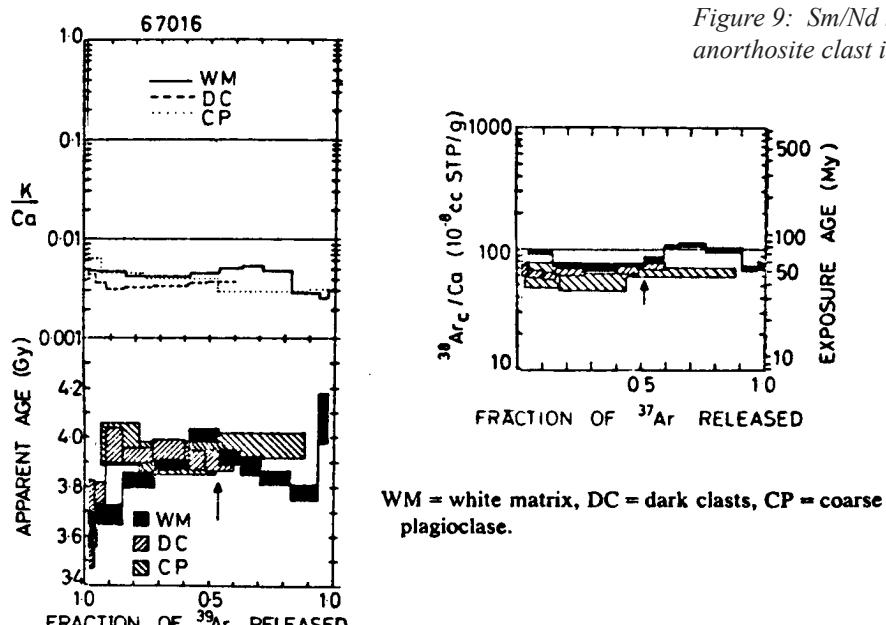
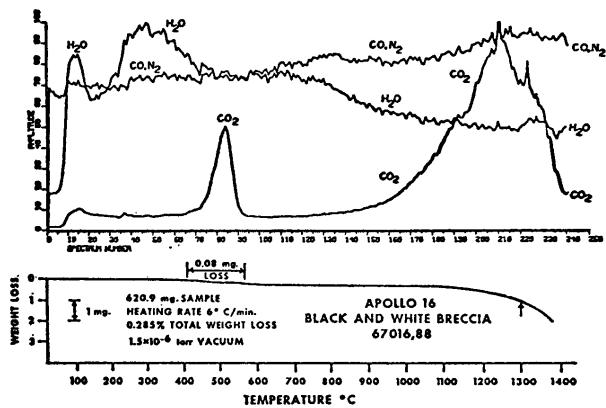


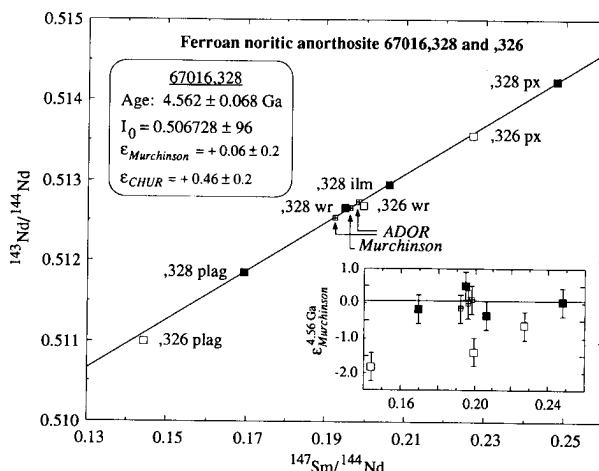
Figure 6: Normalized rare-earth-element diagram for clasts in 67016 studied by Norman and Taylor 1992.



(figure 8) while Alibert et al. found that a ferroan noritic anorthosite clast was as old as 4.562 ± 0.068 b.y. (figure 9).

Cosmogenic isotopes and exposure ages

Turner and Cadogen (1975) determined an ^{38}Ar - ^{37}Ar exposure age of 50 m.y. Eldridge et al. (1975) reported the cosmic-ray induced activity for $^{26}\text{Al}=88$ dpm/kg.,



$^{22}\text{Na}=35\text{dpm/kg.}$ and $^{54}\text{Mn}=15$ dpm/kg. Bhandari et al. (1973) reported track densities and a suntan age of about 1 m.y. and calculate that 67016 has spent less than 15 m.y. within the top 10 cm of the lunar regolith.

Other Studies

Pearce et al. (1973) determined the magnetic properties and found fairly stable remanent magnetization.

Housley et al. (1976) found that this rock did not have significant intensity of FMR (Is/FeO).

Summary of Age Data for 67016

| | Nd/Sm | Ar/Ar |
|-------------------------|-------------------|----------------------|
| Turner and Cadogen 1975 | | 3.95 ± 0.07 b.y. |
| Alibert et al. 1994 | 4.562 ± 0.068 | 3.95 ± 0.07 |

dark clast
plag.
ferroan noritic anorthositic clast

Table 1a. Chemical composition of 67016.

| reference weight | Duncan 73 | Brunfeldt 73 | Taylor 74 | Wanke 76 | Garg 76 | Hertogen 77 | Eldridge 75 482 g | Lindstrom81 bulk |
|---|-----------|--------------|-----------|----------|---------|-------------|----------------------|---------------------|
| SiO ₂ % | 45.25 | (a) | | 44.9 | (d) | 44.8 | (b) | |
| TiO ₂ | 0.44 | (a) | | 0.22 | (d) | 0.35 | (b) | |
| Al ₂ O ₃ | 30.01 | (a) | 30.9 | (b) | 30.1 | (d) | 28.2 | (b) |
| FeO | 3.57 | (a) | 3.7 | (b) | 3.45 | (d) | 3.94 | (b) |
| MnO | 0.051 | (a) | 0.05 | (b) | | | 0.05 | (b) |
| MgO | 3.5 | (a) | 6.8 | (b) | 3.7 | (d) | 4.34 | (b) |
| CaO | 16.85 | (a) | 16.1 | (b) | 16.8 | (d) | 16.73 | (b) |
| Na ₂ O | 0.48 | (a) | 0.55 | (b) | 0.47 | (d) | 0.49 | (b) |
| K ₂ O | 0.06 | (a) | | | 0.06 | (d) | 0.04 | (b) |
| P ₂ O ₅ | 0.072 | (a) | | | | 0.02 | (b) | |
| S % | 0.006 | (a) | | | | 0.019 | (b) | |
| <i>sum</i> | | | | | | | | |
| Sc ppm | | | 6.9 | (b) | 10 | (c) | 6.57 | (b) |
| V | | | 50 | (b) | 23 | (c) | | |
| Cr | | | 440 | (b) | | 540 | (b) | |
| Co | | | | | 15 | (c) | 383 | (b) |
| Ni | 36.7 | (a) | 65 | (b) | 110 | (c) | 10.4 | (b) |
| Cu | | | | | 3 | (c) | | |
| Zn | 4.1 | (a) | | | | | 0.75 | 5.59 |
| Ga | | | | | | | 9.13 | (e) |
| Ge ppb | | | | | | | 6.7 | 77 |
| As | | | | | | | 11.6 | (e) |
| Se | | | | | | | 19.2 | 16.6 |
| Rb | 1.1 | (a) | 0.9 | (b) | 0.71 | (c) | 0.34 | 0.66 |
| Sr | 191 | (a) | 170 | (b) | | 162 | (b) | |
| Y | 15.5 | (a) | | | 15 | (c) | 16 | (b) |
| Zr | 62.5 | (a) | | | 48 | (c) | 46 | (b) |
| Nb | 4.5 | (a) | | | 4.12 | (c) | 77.1 | (b) |
| Mo | | | | | | | | |
| Ru | | | | | | | | |
| Rh | | | | | | | | |
| Pd ppb | | | | | | | 1.3 | 2.09 |
| Ag ppb | | | | | | | 0.75 | 0.69 |
| Cd ppb | | | | | | | 0.49 | 0.68 |
| In ppb | | | | | | | 0.65 | 0.56 |
| Sn ppb | | | | | | | | (e) |
| Sb ppb | | | | | | | 0.2 | 0.26 |
| Te ppb | | | | | | | 89 | 52 |
| Cs ppm | | | 0.04 | (c) | | | 11.2 | 38.8 |
| Ba | 67 | (a) | 65 | (b) | 69 | (c) | 60 | (b) |
| La | | | 3.1 | (b) | 4.52 | (c) | 3.76 | (b) |
| Ce | | | 8.7 | (b) | 12.1 | (c) | 10.1 | (b) |
| Pr | | | | | 1.54 | (c) | | |
| Nd | | | | | 6.25 | (c) | 7.6 | (b) |
| Sm | | | 1.98 | (b) | 1.82 | (c) | 1.64 | (b) |
| Eu | | | 0.86 | (b) | 1 | (c) | 1.06 | (b) |
| Gd | | | | | 2.42 | (c) | | |
| Tb | | | 0.35 | (b) | 0.37 | (c) | 0.33 | (b) |
| Dy | | | | | 2.51 | (c) | 2.11 | (b) |
| Ho | | | | | 0.59 | (c) | | |
| Er | | | | | 1.66 | (c) | | |
| Tm | | | | | 0.26 | (c) | | |
| Yb | | | 1.5 | (b) | 1.6 | (c) | 1.35 | (b) |
| Lu | | | 0.26 | (b) | 0.25 | (c) | 0.19 | (b) |
| Hf | | | 1.5 | (b) | 1.36 | (c) | 1.16 | (b) |
| Ta | | | 0.14 | (b) | | 0.18 | (b) | |
| W ppb | | | | | | | 0.06 | 0.262 |
| Re ppb | | | | | | | 2.71 | 0.2 |
| Os ppb | | | | | | | 1.14 | 0.26 |
| Ir ppb | | | | | 10 | (b) | 2.9 | 2.38 |
| Pt ppb | | | | | | | 2.31 | (e) |
| Au ppb | | | | | 4.8 | (b) | 0.08 | 0.46 |
| Th ppm | | | 0.5 | (b) | 0.73 | (c) | 0.53 | (b) |
| U ppm | | | 0.19 | (b) | 0.17 | (c) | | |
| <i>technique:</i> (a) XRF, (b) INAA, (c) SSMS, (d) e. probe, (e) RNAA, (f) radiation counting | | | | | | | | |

Table 1b. Chemical composition of 67016.

| | bulk sodic ferrogabbro clast | | | | | | |
|--------------------------------|-------------------------------|-------|-----------------------|-------------------------|---------------------|---------------------|-----------------------|
| reference | Lindstrom and Sulpas 1983 (b) | | | | | | |
| SiO ₂ % | 82.4 mg | 289 | melt rock average (8) | anorthosite average (5) | Mg rich average (2) | Fe rich average (2) | granulite average (7) |
| TiO ₂ | | | | | | | |
| Al ₂ O ₃ | 29.4 | 17.4 | 31.3 | 35 | 31.3 | 22.9 | 27.7 |
| FeO | 3.55 | 9.79 | 3.7 | 0.9 | 2.6 | 8.5 | 4.7 |
| MnO | | | | | | | |
| MgO | 3.5 | 4.8 | 3 | 1 | 2.8 | 6.8 | 7.8 |
| CaO | 16 | 15 | 18 | 19.7 | 17.1 | 14.75 | 15.3 |
| Na ₂ O | 0.51 | 0.765 | 0.53 | 0.38 | 0.49 | 0.28 | 0.45 |
| K ₂ O | | | | | | | |
| P ₂ O ₅ | | | | | | | |
| S % | | | | | | | |
| sum | | | | | | | |
| Sc ppm | 6.67 | 36.9 | 7.4 | 1.5 | 5.4 | 21 | 6 |
| V | | | | | | | |
| Cr | 448 | 257 | 474 | 97 | 319 | 1040 | 700 |
| Co | 6.5 | 8.33 | 9.5 | 0.7 | 2.09 | 6.6 | 25 |
| Ni | 60 | 100 | 58 | | | 34 | 260 |
| Cu | | | | | | | |
| Zn | | | | | | | |
| Ga | | | | | | | |
| Ge ppb | | | | | | | |
| As | | | | | | | |
| Se | | | | | | | |
| Rb | | | | | | | |
| Sr | 182 | 170 | 164 | 171 | 193 | 130 | 170 |
| Y | | | | | | | |
| Zr | | | | | | | |
| Nb | | | | | | | |
| Mo | | | | | | | |
| Ru | | | | | | | |
| Rh | | | | | | | |
| Pd ppb | | | | | | | |
| Ag ppb | | | | | | | |
| Cd ppb | | | | | | | |
| In ppb | | | | | | | |
| Sn ppb | | | | | | | |
| Sb ppb | | | | | | | |
| Te ppb | | | | | | | |
| Cs ppm | | | | | | | |
| Ba | 63 | 375 | 38 | 40 | 37 | 33 | 70 |
| La | 3.22 | 23.3 | 2.2 | 0.9 | 1.3 | 1.4 | 4.2 |
| Ce | 9.03 | 66 | 5.8 | 2.5 | 3.3 | 4 | 11.4 |
| Pr | | | | | | | |
| Nd | | | | | | | |
| Sm | 1.57 | 14.7 | 1.1 | 0.42 | 0.6 | 0.96 | 1.95 |
| Eu | 1.07 | 2.41 | 1 | 0.86 | 1 | 0.75 | 1.04 |
| Gd | | | | | | | |
| Tb | 0.365 | 3.95 | 0.28 | 0.09 | 0.14 | 0.27 | 0.45 |
| Dy | | | | | | | |
| Ho | | | | | | | |
| Er | | | | | | | |
| Tm | | | | | | | |
| Yb | 1.33 | 14.7 | 0.95 | 0.27 | 0.5 | 1.16 | 1.7 |
| Lu | 0.192 | 2.15 | 0.14 | 0.04 | 0.08 | 0.18 | 0.25 |
| Hf | 1.38 | 14 | 0.86 | 0.3 | 0.37 | 0.6 | 1.6 |
| Ta | 0.195 | 1.35 | 0.16 | 0.05 | 0.1 | 0.04 | 0.27 |
| W ppb | | | | | | | |
| Re ppb | | | | | | | |
| Os ppb | | | | | | | |
| Ir ppb | | | | | | | |
| Pt ppb | | | | | | | |
| Au ppb | | | | | | | |
| Th ppm | 0.58 | 4.95 | 0.24 | 0.09 | 0.3 | 0.09 | 1.05 |
| U ppm | 0.16 | 1.55 | 0.06 | | 0.05 | 0.06 | |

technique: (b) INAA

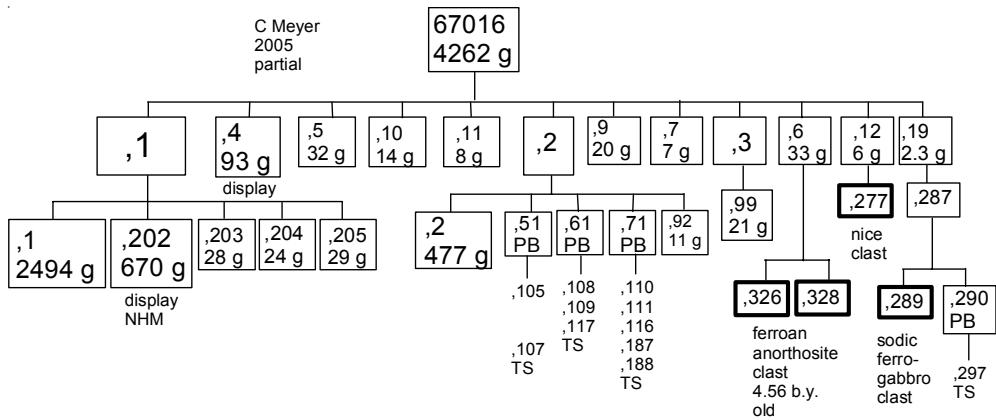
note: numerous analyses of individual clasts are given in Lindstrom and Sulpas 1983.

Table 1c. Chemical composition of 67016.

| | bulk | bulk | bulk | ferroan noritic anorthosite | | |
|--------------------------------|------------------------|------|-------|-----------------------------|-----------|---------------------|
| reference | Norman and Taylor 1992 | | | ,326/8 | ,326/8 | Alibert et al. 1994 |
| weight | 2.2 g | 2.2 | 2.2 | 1.577 g | 1.557 | |
| SiO ₂ % | 44.43 | (d) | | 45.31 | (d) | |
| TiO ₂ | 0.38 | (d) | 0.49 | 0.49 | (g) 0.4 | (d) 0.486 (g) |
| Al ₂ O ₃ | 30.36 | (d) | 29.92 | 30.48 | (g) 26.22 | (d) 25.64 (g) |
| FeO | 3.81 | (d) | 4.78 | 3.69 | (g) 6.56 | (d) 7.96 (g) |
| MnO | 0.05 | (d) | 0.054 | 0.055 | (g) 0.09 | (d) 0.104 (g) |
| MgO | 3.79 | (d) | 3.79 | 3.81 | (g) 5.3 | (d) 5.42 (g) |
| CaO | 16.6 | (d) | 17.27 | 17.44 | (g) 15.81 | (d) 16.04 (g) |
| Na ₂ O | 0.52 | (d) | 0.617 | 0.686 | (g) 0.28 | (d) 0.388 (g) |
| K ₂ O | 0.06 | (d) | 0.05 | 0.047 | (g) 0.02 | (d) 0.02 (g) |
| P ₂ O ₅ | | | | | | |
| S % | | | | | | |
| sum | | | | | | |
| Sc ppm | | 7.5 | 7.5 | (g) | 17.5 | (g) |
| V | | 12.6 | 12.5 | (g) | 23.5 | (g) |
| Cr | | 270 | 192 | (g) | 570 | (g) |
| Co | | 94 | 15 | (g) | 7 | (g) |
| Ni | | 561 | 75 | (g) | 37 | (g) |
| Cu | | 3 | 2 | (g) | 28 | (g) |
| Zn | | | | | | |
| Ga | | | | | | |
| Ge ppb | | | | | | |
| As | | | | | | |
| Se | | | | | | |
| Rb | | | | | | |
| Sr | | 187 | 184 | (g) | 137 | (g) |
| Y | | 17 | 18 | (g) | 9 | (g) |
| Zr | 78 | (c) | 66 | 69 | (g) 30 | (c) 25 |
| Nb | 5 | (c) | | | 2.4 | (c) |
| Mo | | | | | | |
| Ru | | | | | | |
| Rh | | | | | | |
| Pd ppb | | | | | | |
| Ag ppb | | | | | | |
| Cd ppb | | | | | | |
| In ppb | | | | | | |
| Sn ppb | | | | | | |
| Sb ppb | | | | | | |
| Te ppb | | | | | | |
| Cs ppm | | | | | | |
| Ba | 79 | (c) | 72 | 72 | (g) 29 | (c) 25 (g) |
| La | 6 | (c) | | | 2.04 | (c) |
| Ce | 15 | (c) | | | 4.51 | (c) |
| Pr | 1.84 | (c) | | | 0.59 | (c) |
| Nd | 8 | (c) | | | 2.83 | (c) |
| Sm | 1.86 | (c) | | | 0.88 | (c) |
| Eu | 0.95 | (c) | | | 0.77 | (c) |
| Gd | 2.13 | (c) | | | 0.97 | (c) |
| Tb | 0.37 | (c) | | | 0.18 | (c) |
| Dy | 2.51 | (c) | | | 1.22 | (c) |
| Ho | 0.52 | (c) | | | 0.28 | (c) |
| Er | 1.5 | (c) | | | 0.85 | (c) |
| Tm | | | | | | |
| Yb | 1.33 | (c) | | | 0.92 | (c) |
| Lu | 0.15 | (c) | | | 0.04 | (c) |
| Hf | 1.34 | (c) | | | 0.65 | (c) |
| Ta | | | | | | |
| W ppb | | | | | | |
| Re ppb | | | | | | |
| Os ppb | | | | | | |
| Ir ppb | | | | | | |
| Pt ppb | | | | | | |
| Au ppb | | | | | | |
| Th ppm | 0.61 | (c) | | | 0.13 | (c) |
| U ppm | 0.15 | (c) | | | 0.04 | (c) |

technique: (c) SSMS, (d) e. probe (g) ICP, (h) IDMS

note: there are numerous analyses
of additional clasts in 67016 in
Norman and Taylor 1992.



Processing

Ryder and Norman (1979 and 1980) summarized the analytical work to that time. Norman and Garcia (1981) described the pieces of 67016 in “guidebook #5” and

give a full genealogy diagram. This rock sample was never sawn for fear of Pb contamination. Instead the sample was “picked apart”, much like a communion loaf.



Figure 10: Photo of 67016,2. NASA S73-20360. Sample about 3 inches.



Figure 11: Photo of 67016, 9. NASA S80-27407. Sample about 2 inches.